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DIRECT OBSERVATIONS OF HIGHER FREQUENCY DENSITY FLUCTUATIONS IN THE INTERPLANETARY PLASMA

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ABSTRACT

Direct observations from the Ames Research Center plasma spectrometers on Pioneer 6 at 1 a.u. in 1965 December have been used to obtain the power associated with fluctuations in the number density of solar-wind protons in the 10^{-3} to 10^{-2} Hz frequency range. A power-law spectrum of $f^{-1.2\pm0.1}$ is obtained in this frequency range. The extension of the power-law density spectrum based on direct observations to these higher frequencies is consistent with previous extrapolations of both spacecraft and interplanetary scintillation observations and with the dominance of large-scale turbulence in the solar wind. This result is also consistent with direct observations of the solar-wind proton speed and the interplanetary magnetic field.

Subject headings: interplanetary medium — plasmas — solar system — solar wind — turbulence

I. INTRODUCTION

The direct measurement of the role of turbulence throughout our solar system is of twofold importance. It contributes to our understanding of the fundamental physical processes that govern our solar system and to our direct knowledge of the behavior of astrophysical plasmas, of which our solar system is currently the only accessible example. There has been a great deal of discussion in the literature concerning the structure of density fluctuations in the interplanetary medium (see Jokipii 1973 for a recent review). At present there is still a controversy concerning the general shape of the power spectrum associated with density fluctuations. Jokipii and Hollweg (1970), Cronyn (1970), and Lovelace *et al.* (1970) all pointed out that the interplanetary scintillation data are consistent with a power-law density spectrum rather than with the Gaussian spectrum as had been previously inferred (Hewish 1971; Hewish and Symonds 1969). Using the assumption of a Gaussian spectrum, Dennison and Hewish (1967), Cohen *et al.* (1967), Hewish and Symonds (1969), and Hewish (1971) inferred from their observations ($\sim$1 Hz) a dominant scale or correlation length of 100–200 km. By direct observations from *Pioneer 6* of the solar-wind density fluctuations, Intriligator and Wolfe (1970) showed that an $f^{-1.3}$ power-law spectrum was associated with the density fluctuations in the 10^{-4} to 10^{-3} Hz frequency range, and that the scale-size of turbulence at 1 a.u. is at least 10^6 km. This result was consistent with the expectations of Jokipii and Hollweg (1970), and implied that the structure of fluctuations of the number density of solar-wind protons in this frequency interval was similar to that of the magnetic field (Coleman 1966; Jokipii and Coleman 1968) and the solar-wind proton speed (Coleman 1968).

The results presented in this paper indicate that the power-law spectrum associated with fluctuations in the number density of solar-wind protons observed in the 10^{-4} to 10^{-3} Hz frequency range (Intriligator and Wolfe 1970) also extends throughout the 10^{-3} to 10^{-2} Hz frequency range, in agreement with the expectations of Jokipii and Hollweg (1970). These results are consistent with the analyses of Cronyn (1970), Lovelace *et al.* (1970), and Cronyn (1972). These results are also consistent with the power spectra of the solar-wind streaming speed in the 10^{-4} to 10^{-2} Hz frequency range (Intriligator 1974) and the power spectra of the solar-wind flux in the frequency range of 10^{-2} to 10^{+1} Hz obtained by Unti, Neugebauer, and Goldstein (1972).

II. OBSERVATIONS

The solar-wind proton data used for this study were obtained on *Pioneer 6* at $\sim$1 a.u. in 1965 December by the Ames Research Center Plasma Analyzer (Intriligator and Wolfe 1970). The observations were analyzed by using the calibrated instrument transmission function and a least-squares iteration technique to fit the flight data to an isotropic Maxwellian distribution. Each of the data sets used is based on 100 possible points of solar-wind data spaced 51 seconds apart. The power spectra were calculated according to the method of Blackman and Tukey (1959).

Figure 1 shows best-fit curves of power as a function of frequency for the number density of solar-wind protons in the frequency range from 10^{-3} to 10^{-2} Hz for each of the six individual data sets used in this analysis. The "equivalent" number of degrees of freedom (Blackman and Tukey 1959) and the slope of each of these curves are listed in table 1. The power spectra in figure 1 indicate that in the 10^{-3} to 10^{-2} Hz frequency range there is a power-law spectrum associated with fluctuations in the number density of solar-wind protons. The power-law slopes of the individual power spectra are quite similar, but the amplitudes of the power vary more widely, reflecting the real changes in the power level in the 10^{-2} to 10^{-5} Hz frequency range (Intriligator and Wolfe 1970).

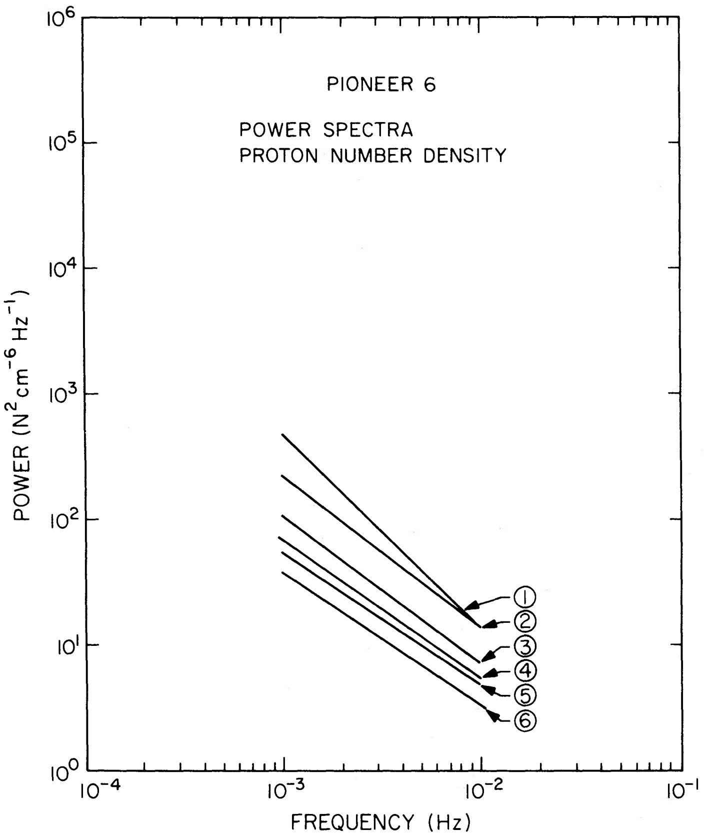

FIG. 1

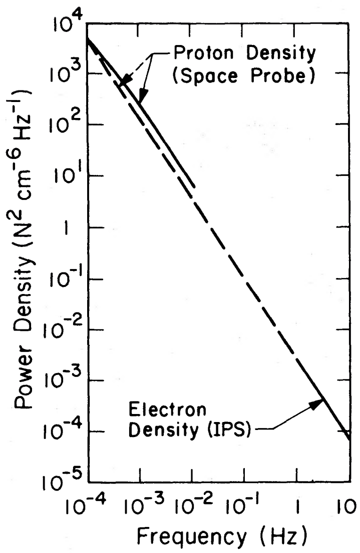

FIG. 2

FIG. 1.—Power spectra of the number density of protons in the solar wind for each of the six data sets listed in table 1.

FIG. 2.—Power spectra of the interplanetary plasma as computed from interplanetary scintillations (Cronyn 1972) at the higher frequencies (see text for a discussion of the controversy concerning the shape of the spectrum at these frequencies) and from direct spacecraft measurements at the lower frequencies. The space probe data in the 10^{-4} to 10^{-3} Hz frequency range are from Intriligator and Wolfe (1972). The space probe data in the 10^{-3} to 10^{-2} frequency range are based on the six data sets shown in fig. 1, where the slope shown was obtained by calculating the mean slope from the slopes of the six data sets, and the amplitude is that associated with data set 3 in fig. 1. There are real variations in the amplitude of the power in this frequency range (see text), with the level of power associated with data set 3 lying approximately midway.

The results presented in figure 1 indicate that the power associated with fluctuations in the number density of solar-wind protons in 1965 December at 1 a.u. in the 10^{-3} to 10^{-2} Hz frequency range follows a power-law spectrum. A mean slope of $f^{-1.2\pm0.1}$ can be calculated (Intriligator and Wolfe 1970) from the six data sets shown. Both the power-law spectra and the amplitudes of the power shown for the six data sets are consistent with our previous lower-frequency (10^{-4} to 10^{-3} Hz) observations (Intriligator and Wolfe 1970). The results presented in figure 1 also indicate that the slope and amplitude of the power associated with fluctuations in the number density of the solar-wind protons in 1965 December at 1 a.u. in the 10^{-3} to 10^{-2} Hz frequency range are consistent with the results obtained (Intriligator 1974) for the slope and amplitude of the power associated with fluctuations in the streaming speed of solar-wind protons in 1965 December at 1 a.u. in the 10^{-3} to 10^{-2} Hz frequency range.

To synthesize our results on the shape and amplitude of the power spectrum associated with fluctuations in solar-wind proton density over the entire range from 10^{-4} to 10^{-2} Hz, we have reproduced in figure 2 the figure from Cronyn (1972) showing the original space-probe data in the 10^{-4} to 10^{-3} Hz frequency range (Intriligator and Wolfe 1970), to which we have added the results in the 10^{-3} to 10^{-2} Hz frequency range calculated from the six data sets shown in figure 1. This figure also indicates Cronyn's interpretation of the interplanetary scintillation (IPS) results on the electron density in the 10^0–10^{+1} Hz frequency range. Cronyn (1972) analyzed this problem in detail by working through all of the numbers in the framework of the thin-screen model. His results indicate that the power spectra of the solar-wind proton number density (Intriligator and Wolfe 1970) in the 10^{-4} to 10^{-3} Hz frequency range, and the interplanetary scintillation spectra deduced from an extrapolation of the Lovelace *et al.* (1970) data in the $\sim 10^0$–10^{+1} Hz frequency range

TABLE 1

RELEVANT PARAMETERS FOR THE SIX DATA SETS USED IN FIGURE 1

Data Set (1)	Date (2)	Equivalent No. of Degrees of Freedom (3)	Slope (4)	Average Number Density of Protons (cm^{-3}) (5)	Average Streaming Velocity ($km\ s^{-1}$) (6)
1......	1965 December 21	18.9	−1.5	7.5	369
2......	1965 December 20	17.5	−1.2	4.4	364
3......	1965 December 20–21	19.3	−1.2	7.9	372
4......	1965 December 21	16.7	−1.1	6.3	350
5......	1965 December 23	15.9	−1.1	4.8	417
6......	1965 December 23	18.7	−1.1	3.4	405

can be related by a power-law spectrum. As discussed above, there is still some controversy as to whether the interplanetary scintillation results are consistent with a power-law spectrum (Jokipii and Hollweg 1970; Lovelace *et al.* 1970; Cronyn 1972) in the 10^0–10^{+1} Hz frequency range, or whether they are only consistent with a Gaussian shaped spectrum (Hewish 1971) in this $\sim 10^0$–10^{+1} Hz frequency range. In contrast, it should be noted that the uncertainty is very small ($f^{-1.3\pm0.1}$ and $f^{-1.2\pm0.1}$, respectively, in the 10^{-4} Hz to 10^{-3} Hz frequency range and in the 10^{-3} Hz to 10^{-2} Hz frequency range) in the slope of the power spectrum obtained from the direct space-probe observations. As discussed above, there is a real variation in the amplitude of the power in the 10^{-4} Hz to 10^{-2} Hz frequency range associated with real changes in the solar-wind fluctuations at these frequencies. For example, the ranges of the levels of power associated with the six individual power spectra in figure 1 vary by more than one order of magnitude with the levels of power associated with data set 3 lying approximately midway. The levels of power associated with data set 3 in figure 1 were used in figure 2 to represent the power-law spectrum in the 10^{-3} Hz to 10^{-2} Hz frequency range. This implies, therefore, that there is a real variation of approximately one order of magnitude in the amplitude of the line shown in figure 2 in the 10^{-4} to 10^{-2} Hz frequency range, but essentially *no* variation in slope.

The measured power-law shape of the power spectrum within the frequency range 10^{-4} to 10^{-2} Hz associated with fluctuations in the solar-wind proton number density argues for the dominance of large-scale turbulence in the solar wind. That is, the upward slope of the power-law spectrum at 10^{-4} Hz provides an indication that the scale-size of turbulence is at least 10^6 km (0.01 a.u.), i.e., the 10^{-4} Hz characteristic frequency, f, can be associated with a characteristic length scale ($L = 1/q = \frac{1}{2}V_w/\pi f$, where V_w is the solar-wind speed and q the wavenumber). The power-law spectrum over the 10^{-4} Hz to 10^{-2} Hz frequency range, therefore, implies that the integral of the power associated with the 10^{-4} Hz to 10^{-2} Hz portion of the curve is many orders of magnitude larger than that associated with the integral of the power associated with the 10^0–10^{+1} Hz frequency range of the interplanetary scintillation measurements. The specific shape of the spectrum associated with solar-wind number density fluctuations in the 10^{-2} Hz to 10^{+1} Hz frequency range has not been measured; however, at present there is some indirect evidence based on the fluctuations in the solar-wind proton flux (Unti *et al.* 1972) that the basic shape of the spectrum is as extrapolated in figure 2.

III. SUMMARY

A problem of considerable importance to the understanding of the physics of the interplanetary medium is the relationship between the small-scale structure associated with fluctuations in the interplanetary electron density as deduced from the interplanetary scintillation spectra of compact radio sources, and the larger-scale structure based on direct observations from spacecraft. In this paper we have extended to higher frequencies (10^{-3} to 10^{-2} Hz) the direct observations from spacecraft at 1 a.u. in the ecliptic plane. These results indicate that in 1965 December there is a power-law spectrum associated with fluctuations in the number density of solar-wind protons throughout the 10^{-4} Hz to 10^{-2} Hz frequency range. The data indicate a frequency dependence of $f^{-1.2\pm0.1}$ in the 10^{-3} to 10^{-2} Hz frequency range. There is a real variation in the levels of power associated with the fluctuations in the number density of solar-wind protons in the 10^{-5} to 10^{-2} Hz frequency range. These variations in amplitude are a manifestation of the high speed stream structure and other lower frequency variations in the solar wind (Intriligator and Wolfe 1970; Jokipii 1973).

The slope and amplitude of the power-law spectra associated with fluctuations in the number density of solar-wind protons in the 10^{-3} to 10^{-2} Hz frequency range shown in figures 1 and 2 are consistent with the results for the fluctuations in the number density of the solar-wind protons at lower frequencies (10^{-4} to 10^{-3} Hz). These results are consistent with the power-law spectrum associated with direct observations of the fluctuations in the solar-wind streaming speed (Intriligator 1974) and with the power spectra obtained from direct observations of the interplanetary magnetic field fluctuations (Coleman 1966; Jokipii and Coleman 1968). These results are also consistent with the expectations of Jokipii and Hollweg (1970) and Cronyn (1972). Cronyn (1972) discussed the relationship between the small-scale structures associated with fluctuations in the interplanetary electron density as deduced from the interplanetary scintillation spectra of compact radio sources, and the larger-scale structure based on direct observations from spacecraft. Figure 2 shows the inclusion of our higher frequency (10^{-3} to 10^{-2} Hz) results in the figure from Cronyn (1972). Figure 2 clearly shows that the power-law spectrum in the 10^{-3} to 10^{-2} Hz frequency range is consistent with Cronyn's analysis. The amplitude of the power spectrum of the solar-wind proton number density in figures 1 and 2 is also consistent with Cronyn's results. The existence of a power-law spectrum for the structure of solar-wind fluctuations between 10^{-4} to 10^{-2} Hz in the ecliptic plane at ~ 1 a.u. argues strongly for the dominance of large-scale turbulence in the solar wind. If there is a smooth power-law spectrum associated with solar-wind fluctuations from these frequencies through the higher frequencies associated with the interplanetary scintillation observations, then this argues even more strongly for the dominance of large-scale turbulence in the solar wind. Further observational and theoretical studies of the structure of solar-wind fluctuations at all frequencies at various times throughout the solar cycle and at various locations in the solar system (including out of the ecliptic plane) should substantially add to our understanding of the structure of turbulence and its astrophysical effects.

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